

Wavelength Calibration Standards for the WDM L-Band*

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Abstract

We describe National Institute of Standards and Technology research on wavelength standards for the optical communications L-band. We are developing a pair of transfer standards that can be used to calibrate the wavelength scale and scan linearity of instruments in the 1565 to 1630 nm region. The two transfer standards are based on carbon monoxide absorption cells with absorption spectra in this spectral region. We describe and quantify the process by which we determine the centers of the absorption lines and the mechanisms that limit their accuracy.

Introduction

Wavelength division multiplexing (WDM) is expanding into the spectral region between 1565 and 1625 nm (often referred to as the L-band) due to the need for more bandwidth and the advent of the long-band erbium amplifier. This has introduced a need for instrumentation in the L-band, as well as a means to calibrate the instrumentation. This expansion of WDM into longer spectral regions follows the prediction that WDM will ultimately fill the entire useful optical fiber transmission band from about 1280 to 1630 nm and bring with it the need for instrumentation and calibration aids throughout this region.

Atomic and molecular absorption and emission spectra provide stable spectral references that have well understood physical behavior and are insensitive to environmental changes. Examples of this are molecular rotational-vibrational combination or overtone transitions in acetylene¹ or hydrogen cyanide.² These two gases have strong absorption spectra conveniently located in and near the fiber-optic C-band between 1510 and 1560 nm and are useful for performing calibrations in this region. Other molecules with strong, simple absorption spectra located between 1300 and 1600 nm include hydrogen and deuterium halides and other diatomic molecules such as carbon monoxide. Several hydrocarbons and other compounds have absorption spectra in the desired region but these molecules often have weak or convoluted spectra. Atomic absorptions in the region are limited to excited-state transitions, which require electric discharge³ or laser excitation.⁴ The only laser reference in this region is a helium-neon line at 1523 nm. Other atomic or molecular references can be realized by frequency doubling 1300-1600 nm light to probe atomic transitions in the 650-800 nm region.⁵

NIST L-band transfer standards

We are developing NIST Standard Reference Material (SRM) transfer standards for the WDM L-band based on rotational-vibrational transitions of carbon monoxide (CO). SRM 2516, which will cover the spectral region between 1565 and 1595 nm, is based on the 3v overtone transition of ¹²C¹⁶O; and SRM 2515, which will cover the region between 1595 and 1630 nm, is based on the 3v overtone transition of ¹³C¹⁶O. These two spectra (Fig. 1) are

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nearly identical except for the 35 nm shift to longer wavelength of the $^{13}\text{C}^{16}\text{O}$ spectrum. Each spectrum contains approximately 30 lines of sufficient strength to be used as calibration references.

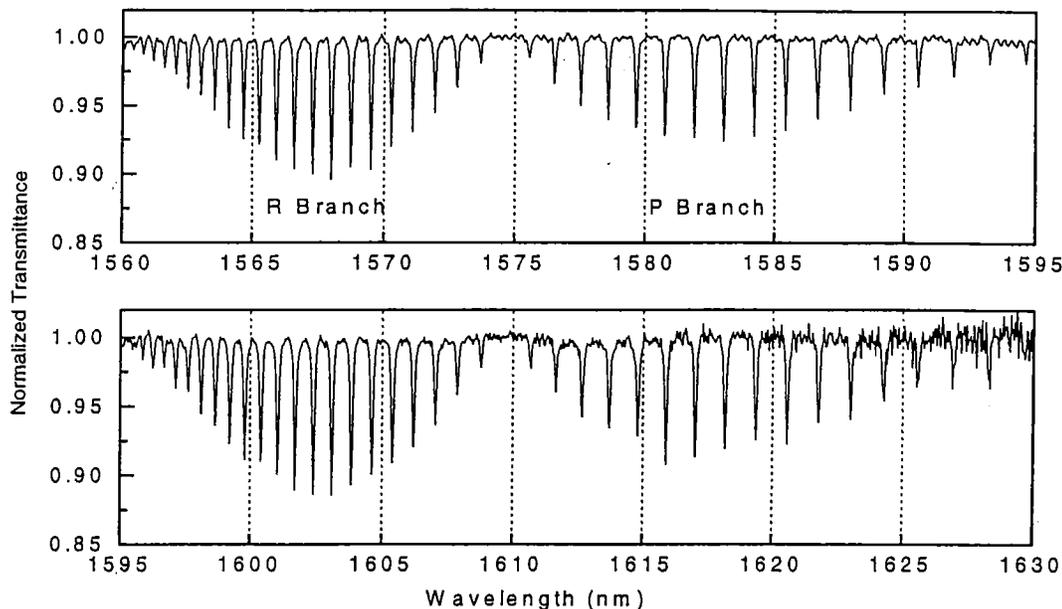


Figure 1 Carbon monoxide spectrum taken by passing LED light through an SRM unit and recording the spectrum of the transmitted light using an optical spectrum analyzer with 0.1 nm resolution. The figure shows the recorded spectrum divided by the LED spectrum. The CO gas pressure is 133 kPa; light makes four passes through the cell for a total optical path length of 80 cm. The upper plot shows the $^{12}\text{C}^{16}\text{O}$ spectrum, and the lower plot shows the $^{13}\text{C}^{16}\text{O}$ spectrum. The lower spectrum is noisier due to lower power from the LED.

The SRMs are designed for calibrating wavelength measuring instrumentation such as optical spectrum analyzers (OSA), tunable diode lasers, and wavelength meters. The unit consists of a hermetically sealed gas absorption cell coupled to single-mode optical fiber. The spectrum can be observed on an OSA by passing light from a broadband source (such as a light-emitting diode or spontaneous-emission source) through the SRM unit and into the OSA. Similarly, the spectrum can be probed with a tunable laser and a detector. Single wavelength calibrations using a single line, and scan linearity measurements using multiple lines can be made. The strongest lines in the CO SRM spectra have a depth of only about 10 %, compared to about 50 % in NIST's HCN-based SRM 2519. However, with a reasonable signal-to-noise ratio this absorption should be strong enough to provide accurate calibration. We have evaluated the uncertainties of the line centers and will provide certified values. Each SRM unit will be measured at NIST to assure that its line centers are within the limits of the NIST certified value and uncertainty.

Measurements

The vacuum wavelengths of several $^{12}\text{C}^{16}\text{O}$ line centers have been measured,^{6,7} with one author quoting an uncertainty of 7×10^{-6} nm.⁶ No accurate measurements of the vacuum wavelength of $^{13}\text{C}^{16}\text{O}$ line centers have been made to date; however, the predicted line centers are reported in the HITRAN database.⁸ The line center values given in Refs. 6 through 8 are for very low pressures, however, and are applicable to within their uncertainties only for those conditions. To provide maximum sensitivity when used with a 0.05 nm resolution instrument, such as an OSA, the gas in the carbon monoxide SRM is at a higher

pressure, about 133 kPa (1000 Torr). This higher pressure induces collisional broadening or "pressure broadening" of the absorption lines; we chose this pressure to obtain a linewidth of about 0.05 nm. This higher pressure also slightly shifts the line centers. This shift, resulting from energy-level shifts caused by the interaction of molecules during collisions, increases linearly with pressure and is often called the pressure shift. Since our goal is to certify the SRM references with an uncertainty of less than 1 pm, we measured the pressure shift of the two isotopes of CO. We also extrapolated to zero pressure the line centers of the lines we measured and compared those values with literature values.

In our measurements, we sent light from a tunable diode laser through two absorption cells simultaneously and monitored the transmittance with two detectors. One cell had a lower pressure (about 26 kPa) and the other a higher (about 133 kPa) pressure. Fluctuations in laser power, monitored by a third detector, were divided out. We used a wavelength meter to monitor the wavelength of the laser as it was scanned across individual absorption lines. We calibrated this wavelength meter periodically during the measurement using a laser locked to

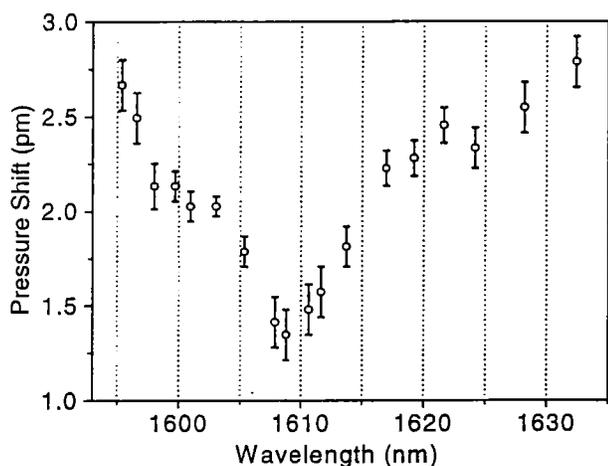


Figure 2 $^{13}\text{C}^{16}\text{O}$ pressure shift at the SRM pressure of 133 kPa (1000 Torr).

a rubidium saturated absorption spectrometer.¹ This calibration improved on the wavelength meter's specified uncertainty of 0.16 pm by removing a constant offset and slow drifts. We normalized the individual line scans, converted them to absorbance spectra, and fitted them with Voigt line shapes to determine the line centers. We determined the pressure shift from the difference between the high and low pressure line centers, and from this we determined the pressure shift coefficient and the extrapolated zero-pressure line center.

We measured the line centers and pressure shifts of 14 lines in the $^{12}\text{C}^{16}\text{O}$ spectrum and of 18 lines in the $^{13}\text{C}^{16}\text{O}$ spectrum (Fig. 2). We found that the pressure shift at the SRM pressure of 133 kPa varied between 1 and 3 pm, depending on the line number, and was slightly larger for $^{13}\text{C}^{16}\text{O}$. Our pressure shift coefficient values for $^{12}\text{C}^{16}\text{O}$ agree well with, and have a lower uncertainty, than those reported by Picque and Guelachvili.⁶ They also agree with the R branch shift coefficients reported by Henningsen, et al⁷ (Henningsen did not report values for the P branch). Our $^{12}\text{C}^{16}\text{O}$ zero-pressure line centers show good agreement, within our uncertainties, with Picque, Henningsen, and the HITRAN database.⁸ Our shift coefficient and zero-pressure line center uncertainties are due primarily to background noise in the line scans. Wavelength meter uncertainty also contributes slightly to the zero-pressure line center uncertainties. There is very little data reported in the literature on the $^{13}\text{C}^{16}\text{O}$ reference lines. The only line center data we have found is in the HITRAN database, and we have found no work reporting $^{13}\text{C}^{16}\text{O}$ pressure shift coefficients. Our $^{13}\text{C}^{16}\text{O}$ zero-pressure line centers show good agreement with the HITRAN data.

For SRM 2516 we derived the line centers by adding the pressure shift (at 133.3 kPa) to the zero-pressure line center values in Ref. 6, and for SRM 2515 we added the pressure shift to the values reported in Ref. 8. For the SRM certification we will certify the wavelengths with

an expanded uncertainty (coverage $k = 2$, that is $\pm 2\sigma$) of about 0.5 pm. Lines for which we did not measure a shift coefficient will be certified with a higher uncertainty due to the pressure shift uncertainty.

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